Status of NASA's Electric Machines R&D for Aeronautics Applications

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Motivation

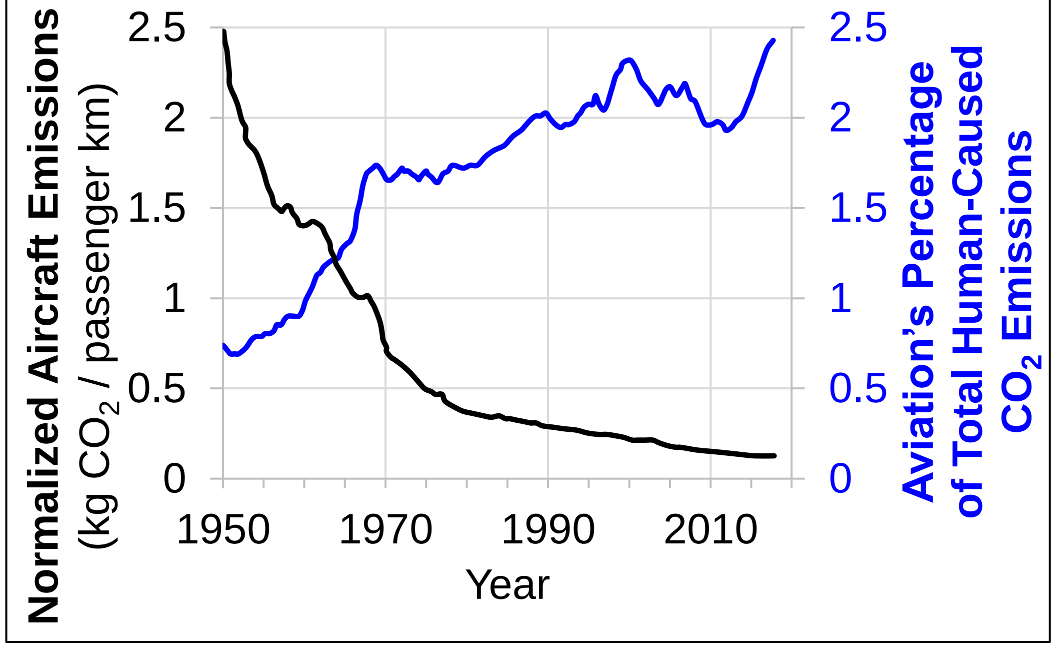
- Aviation impacts:

<u>Climate</u>
- **CO_2** (dominant), **contrails** (~$\frac{1}{2}$ impact of CO_2), **H_2O vapor, soot**

<u>Environment</u>
- Air quality – **NO_x** (dominant), **sulfur**
- Noise

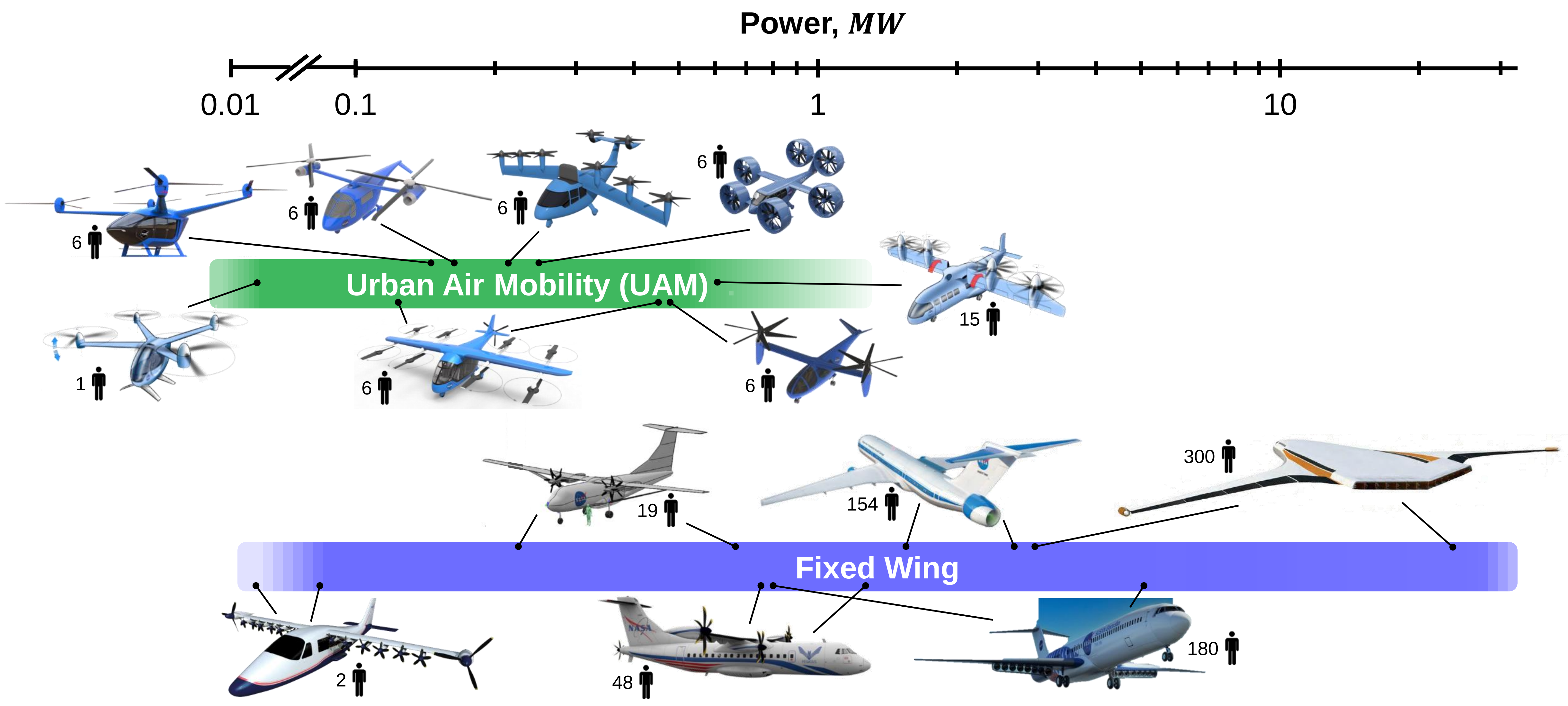
- Despite significant progress in efficiency, global CO_2 emissions from aviation growing at increasing rate
- 2 options:
  - Change fuel (e.g., jet A → SAF or H_2)
  - Electrify

Global aviation impact on CO_2 (data from [1])

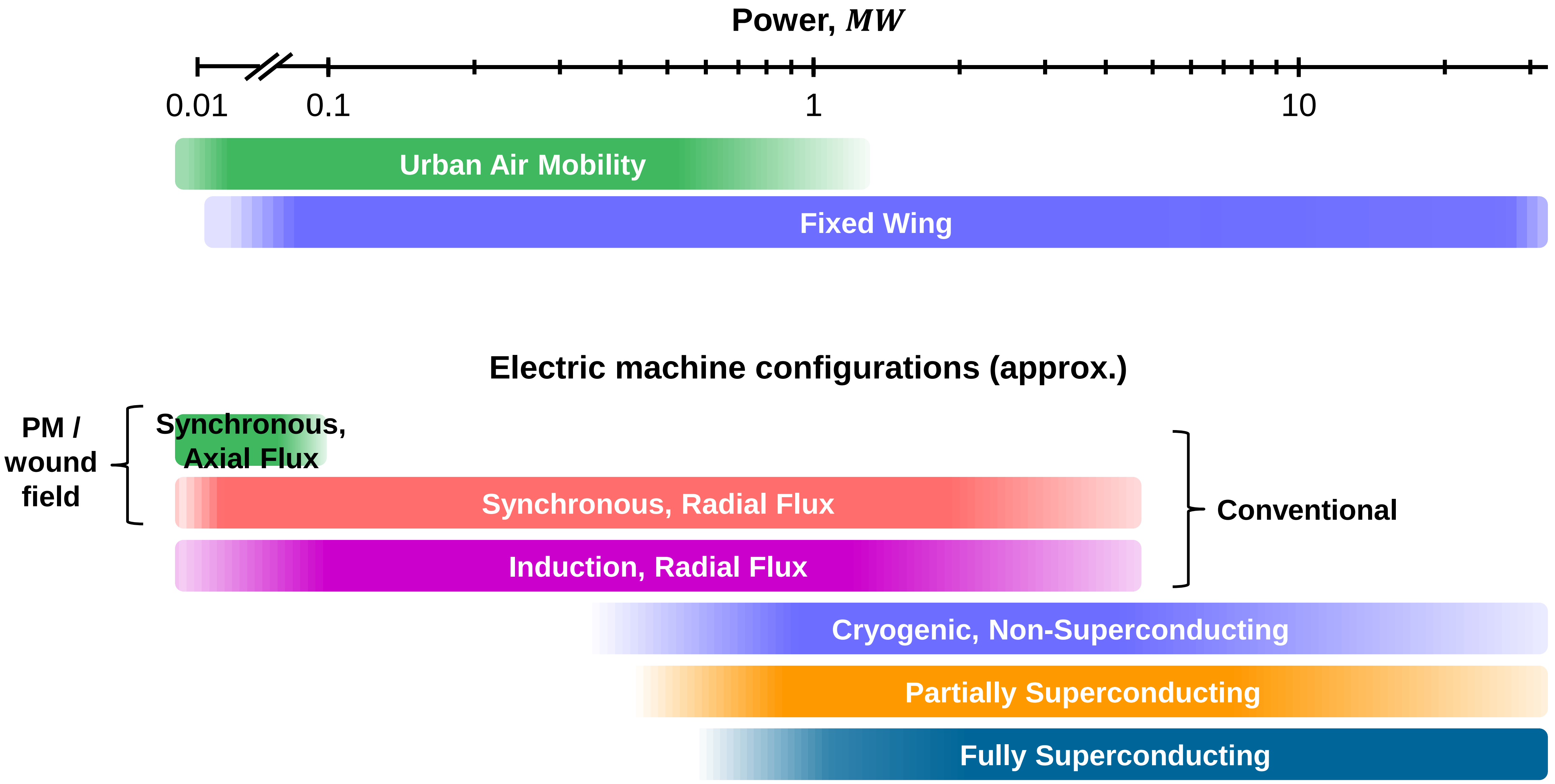


1. Lee, D.S. et al., Atmospheric Environment 244, 117834, 2021.

What Scale of Electric Machine is Relevant?



What Types of Electric Machines are Relevant?



Summary of Select NASA Efforts

Electric machines

Development / experimental projects

- High efficiency megawatt motor – HEMM (1.4 MW partially superconducting)
- Cryocooler compressor motors (2 kW & 20 kW)
- Stator winding reliability / partial discharge
- OSU / U. Wisconsin fault-tolerant integrated modular motor drive – IMMD (1 MW, 2 kV, 20,000 rpm)

Design projects

- 5 MW partially superconducting machine

Electrical power system

Development / experimental projects

- 250 kW inverter (1 kV)
- Resonant inverter (14 kW, 500 V)
- Immersion liquid cooled inverter – MAGIC (40 kW, 270 V)
- DC bus power quality & related standards

Design projects

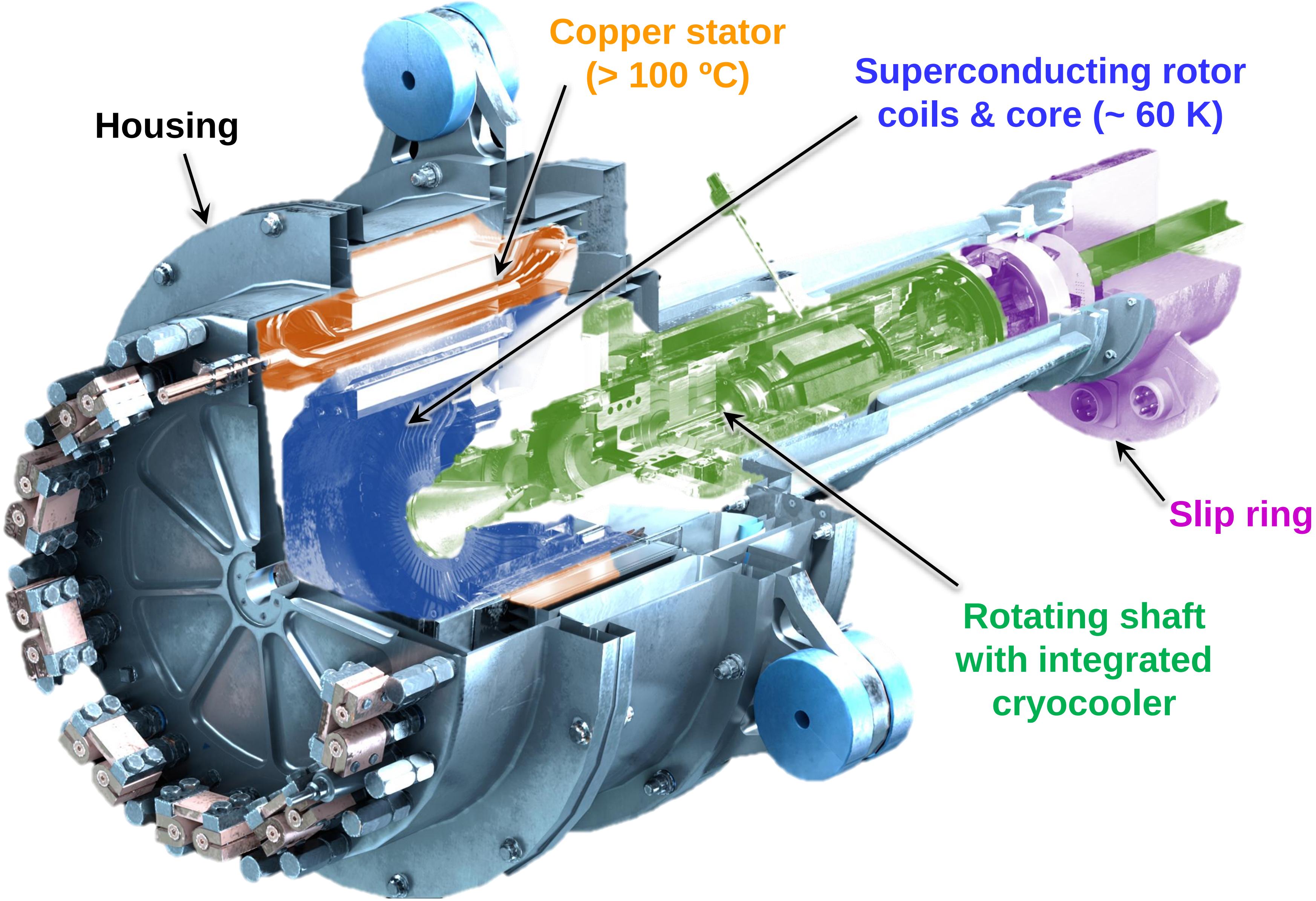
- Resonant inverter with very low THD output for low inductance, loss-sensitive superconducting machines

(green)	= application to fixed wing aircraft (1+ MW components)
(purple)	= application to vertical lift aircraft (~100 kW components)

Large Transport Aircraft Superconducting Machines

NASA's High-Efficiency Megawatt Motor (HEMM)

Parameter	Value
Rated continuous power	1.42 MW
Nominal speed	6,800 rpm
Tip speed	107 m/s
Rated torque	2 kNm
Electromagnetic specific power goal	16 kW/kg
Efficiency goal	> 98%

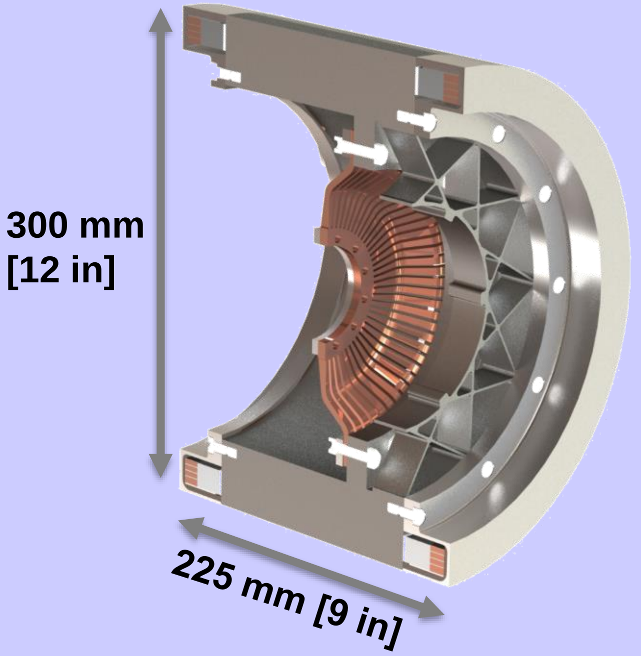


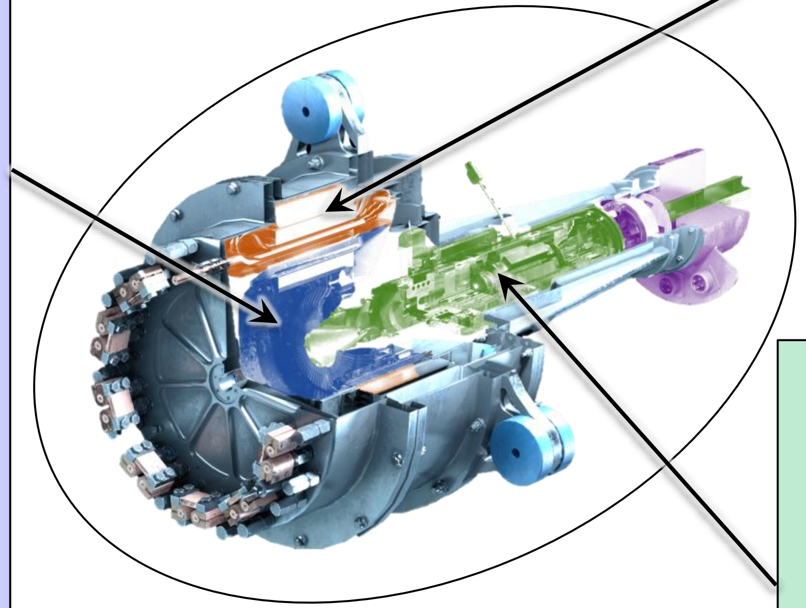
Stator, rotor, & cryocooler being developed in house

Key Requirements of Each Subsystem

Rotor

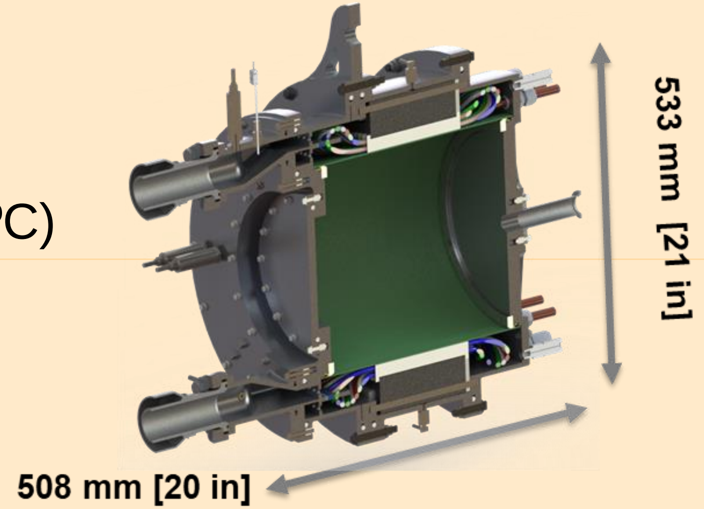
- Maintain coils below 62 K and sustain thermal cycling
- Sustain 6,800 rpm & 2 kNm





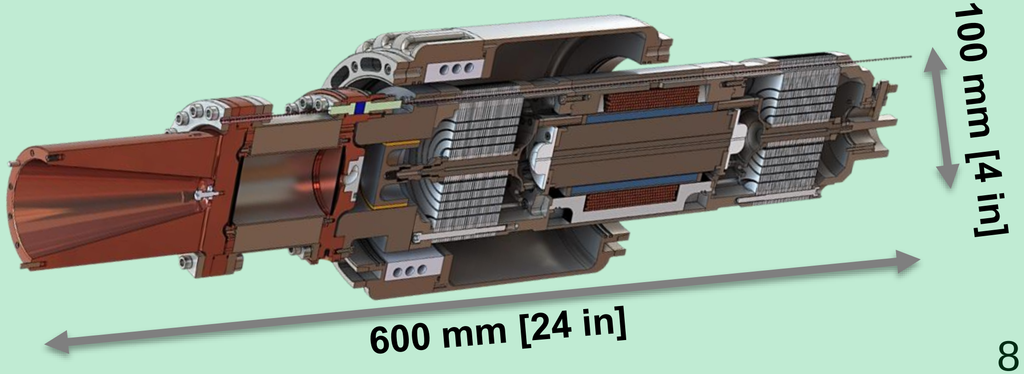
Stator

- Operate up to 500 A rms
- Minimize temperature (limit: 200 ºC)



Cryocooler

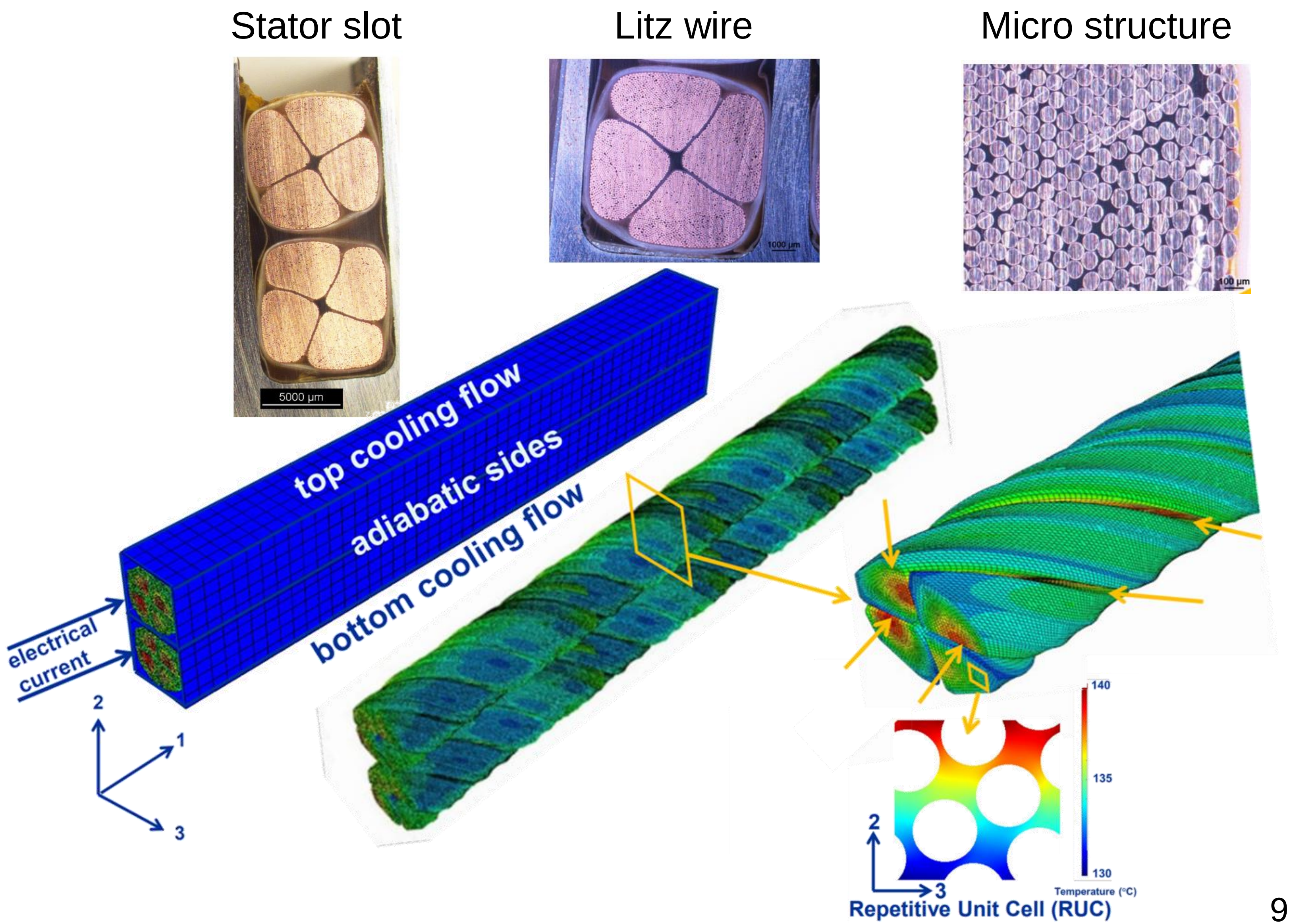
- Extract 50 W of heat from 50 K to 60 ºC
- Use ≤ 2 kW input power



Prior Work on HEMM Stator

Multi-scale thermal modeling [2-4]

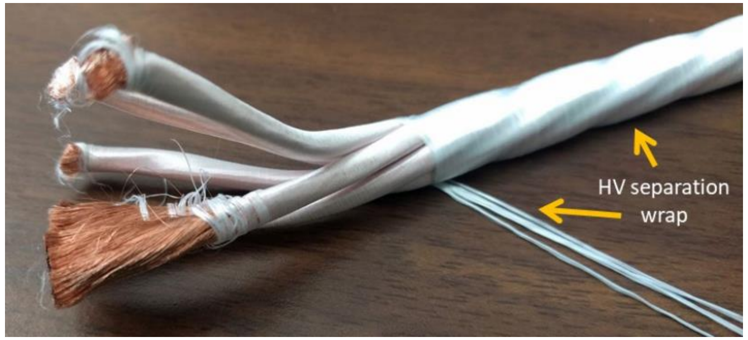
- Outer hot spots can be 10 ºC higher than interior hot spots
- Outer hot spots are not homogeneous



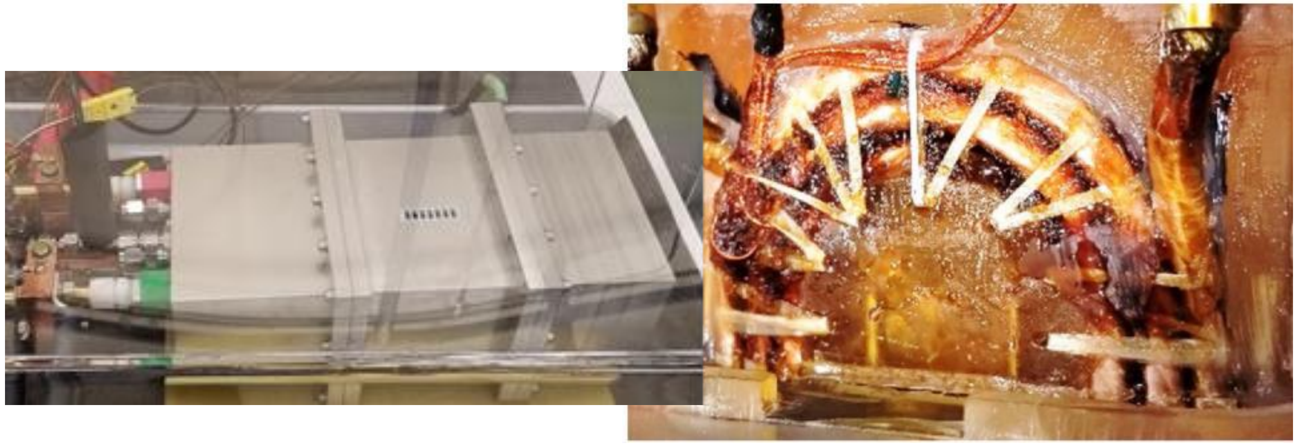
2. Woodworth, A. A. et al., Proc. of AIAA/IEEE Electric Aircraft Technologies Symposium (EATS), 2019.
3. Woodworth, A. A. et al., Proc. of AIAA/IEEE Electric Aircraft Technologies Symposium (EATS), 2021.
4. Woodworth, A. A. et al., Energy & Mobility Conference, 2023.

Prior Work on HEMM Stator

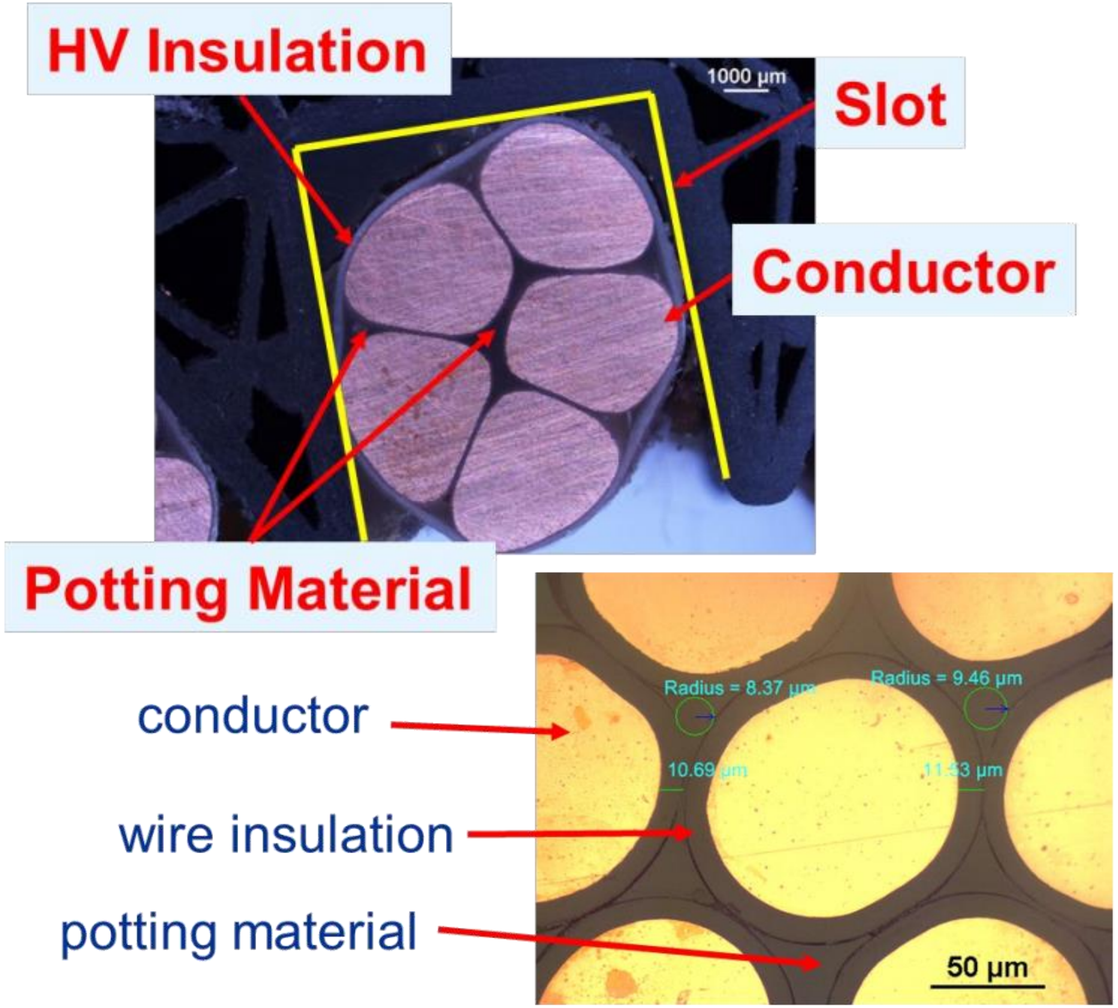
Epoxy vacuum pressure impregnation development & Statorette testing [4,5]



Litz wire used in HEMM containing 6000 AWG 40 (~80 μm diameter) wires



Statorette 3 of 3

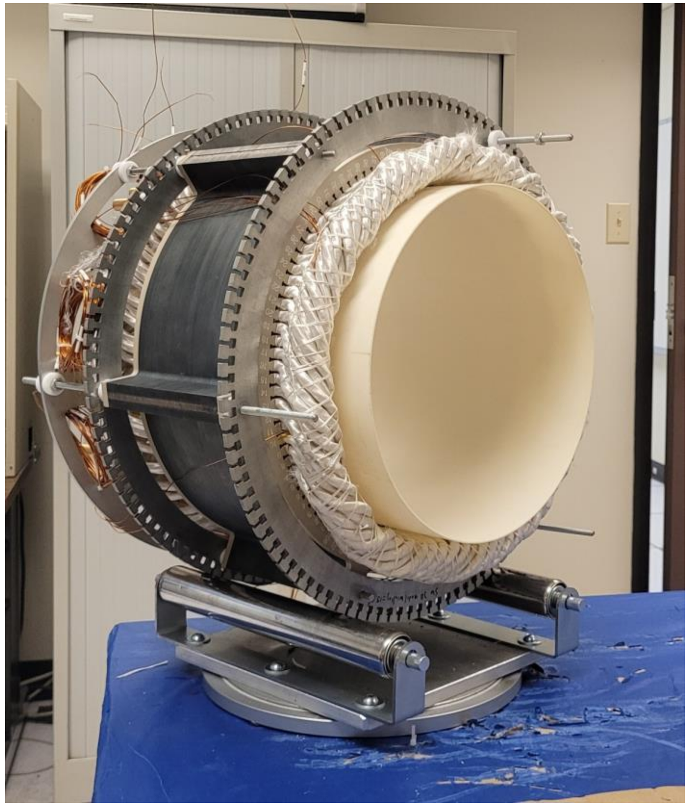


Cross-sections of winding trial showing multi-scale epoxy potting

5. Woodworth, A. A. et al., Proc. of AIAA/IEEE Electric Aircraft Technologies Symposium (EATS), 2020.

Recent Progress on HEMM Stator

- Completed complicated winding of 9 phase stator (picture 1); geometry of wires falls within design limits
- Completed epoxy potting of stator using in-house vacuum pressure impregnation chamber and temperature-pressure-time schedule developed through prior statorette builds and inspections (picture 2)
- Installed stator in liquid-cooled housings and around the vacuum tube for the superconducting rotor (picture 3)



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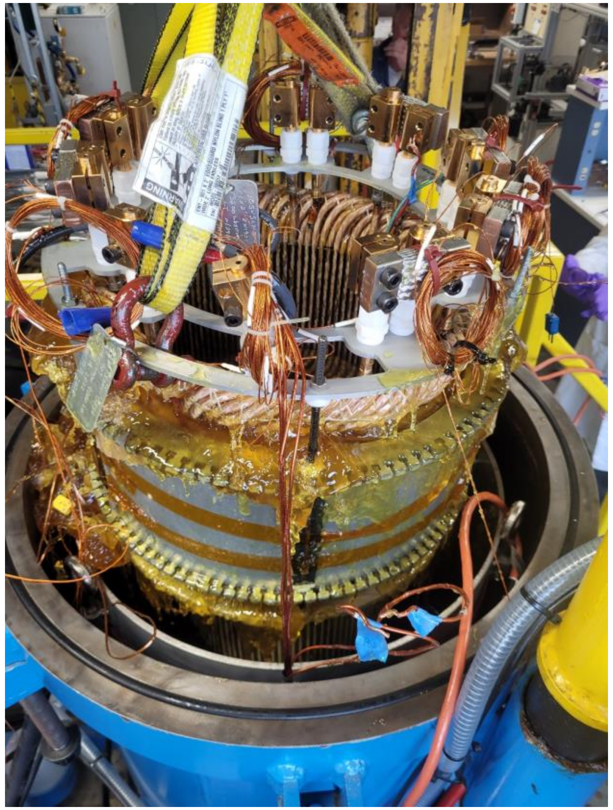

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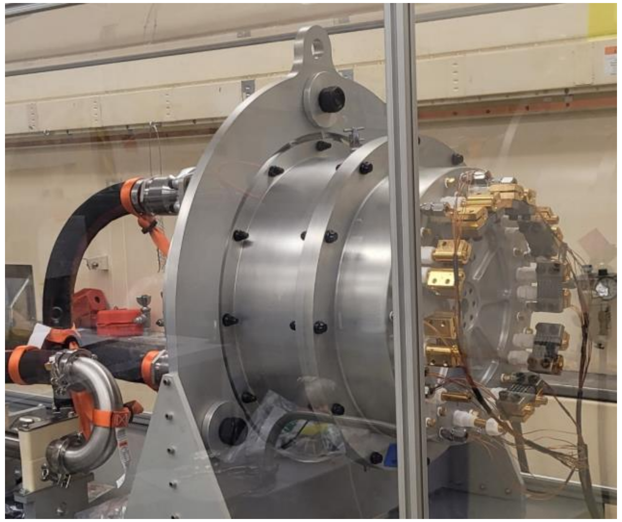
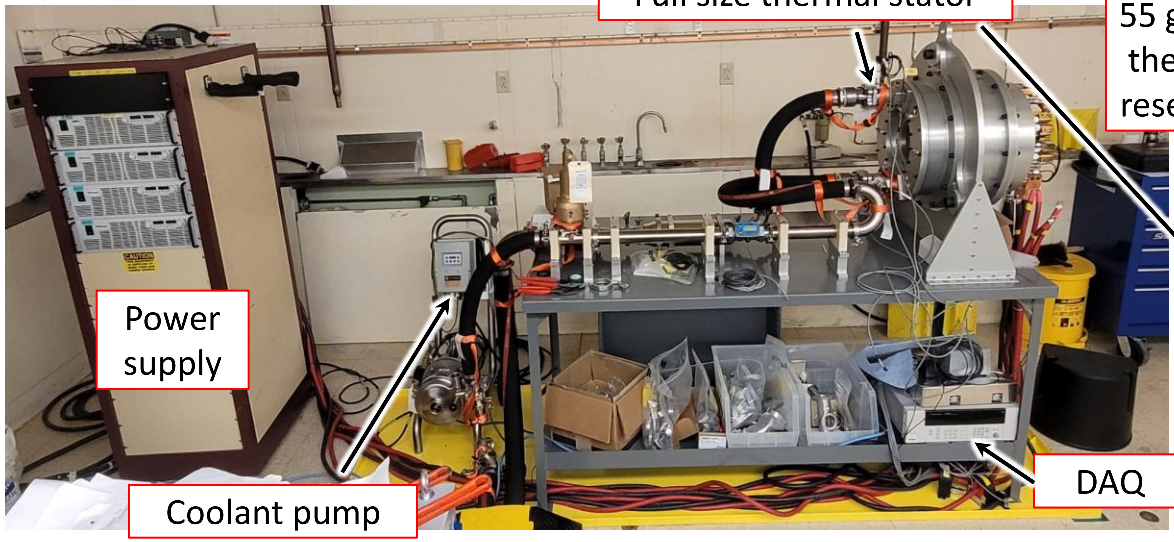
3

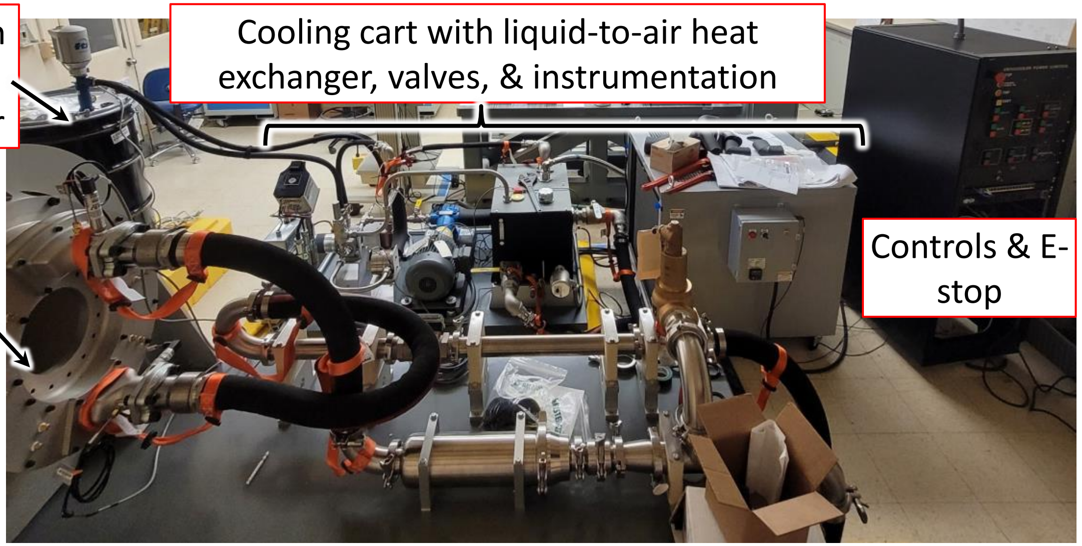
Recent Progress on HEMM Stator

- Stator design objectives: ≤ 220 ºC winding temperature for 434 A rms with 60 ºC coolant at inlet
- **Successfully completed thermal test of full-scale stator** (rotor not installed) [6]
  - Objectives: ≥ 500 A dc, up to 200 ºC peak winding temp., up to 100 gpm flow
  - Reached 500 A at 50 gpm with 191 ºC winding hot spot ▪ pressure drop very low & within expected range ▪ thermal conductivity for winding system within expectations (in-house potting process was successful)



Full-scale stator in thermal test rig





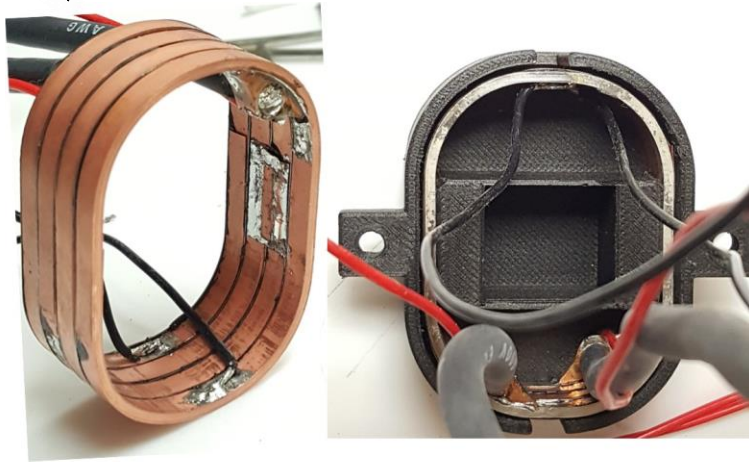
6. Woodworth, A. A. et al., Proc. of AIAA/IEEE Electric Aircraft Technologies Symposium (EATS), 2024. (to appear)

Prior Work on HEMM Rotor

Risk reduction testing of superconducting coils [7-9]

Coils under high-speed rotation
(Feb ’20)

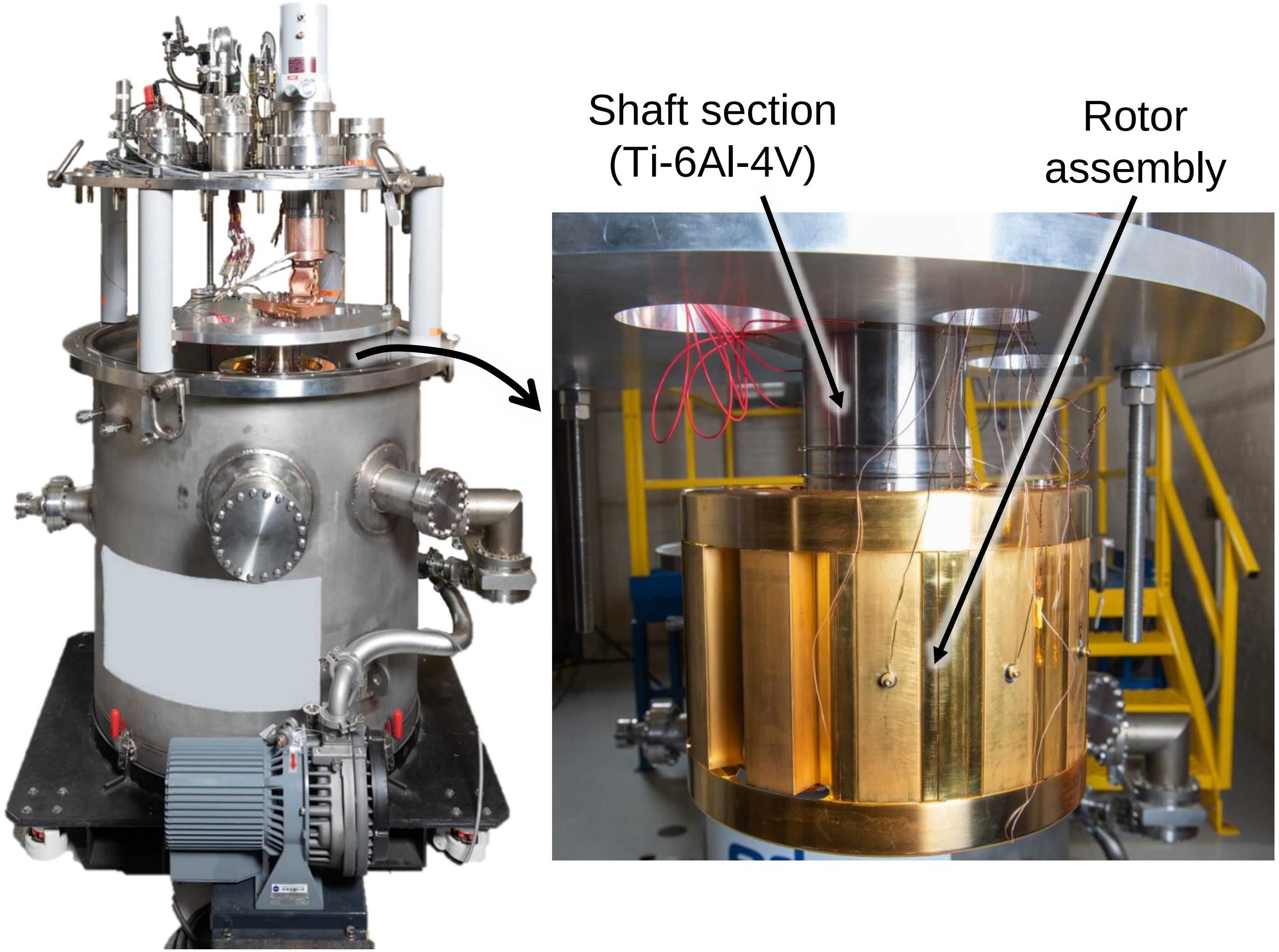
Fabrication & thermal cycling of coils
(Feb ‘19)



7. Scheidler, J.J. and Tallerico, T.F., “High Efficiency Megawatt Motor (HEMM) Test Report…,” NASA/TM-20230017048, 2024. (in press)
8. Scheidler, J.J. et al., “High Efficiency Megawatt Motor (HEMM) Test Report…,” NASA/TM-20230017031, 2024. (in press)
9. Scheidler, J.J. et al., Proc. of AIAA SciTech Forum, 2022.

Recent Progress on HEMM Rotor

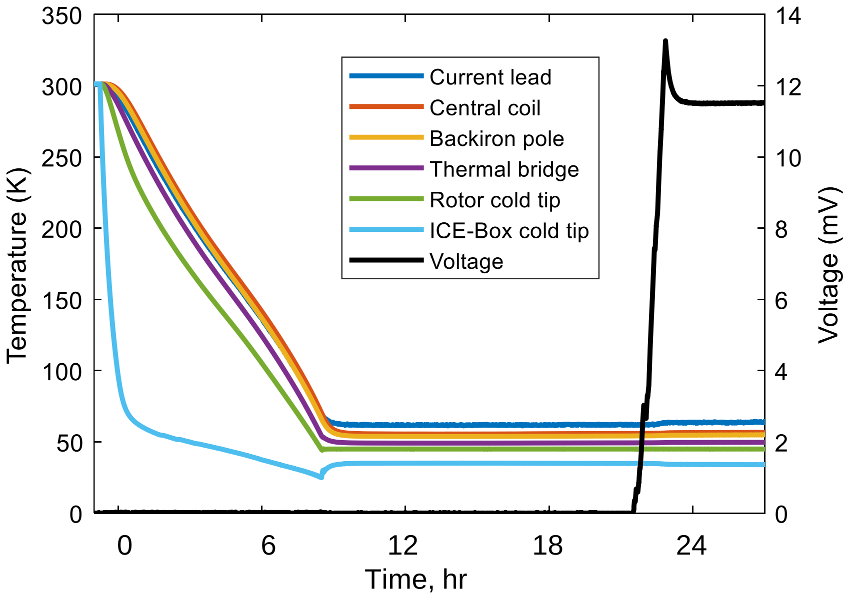
- **Successfully completed testing of full-scale HEMM rotor** in GRC's ICE-Box test rig [10-12]
  - Rotor assembly sustained a total of 6 thermal cycles from 293 K to < 50 K
  - Stable operation of the superconducting coils up to ≥ 45 A (design current = 57.2 A) achieved in 6 separate tests
  - Voltage responses & inductance estimates suggest coils are healthy, but discrepancy in coils' resistance suggests inconsistency in in-house solder joints and/or degradation to some of the superconductor



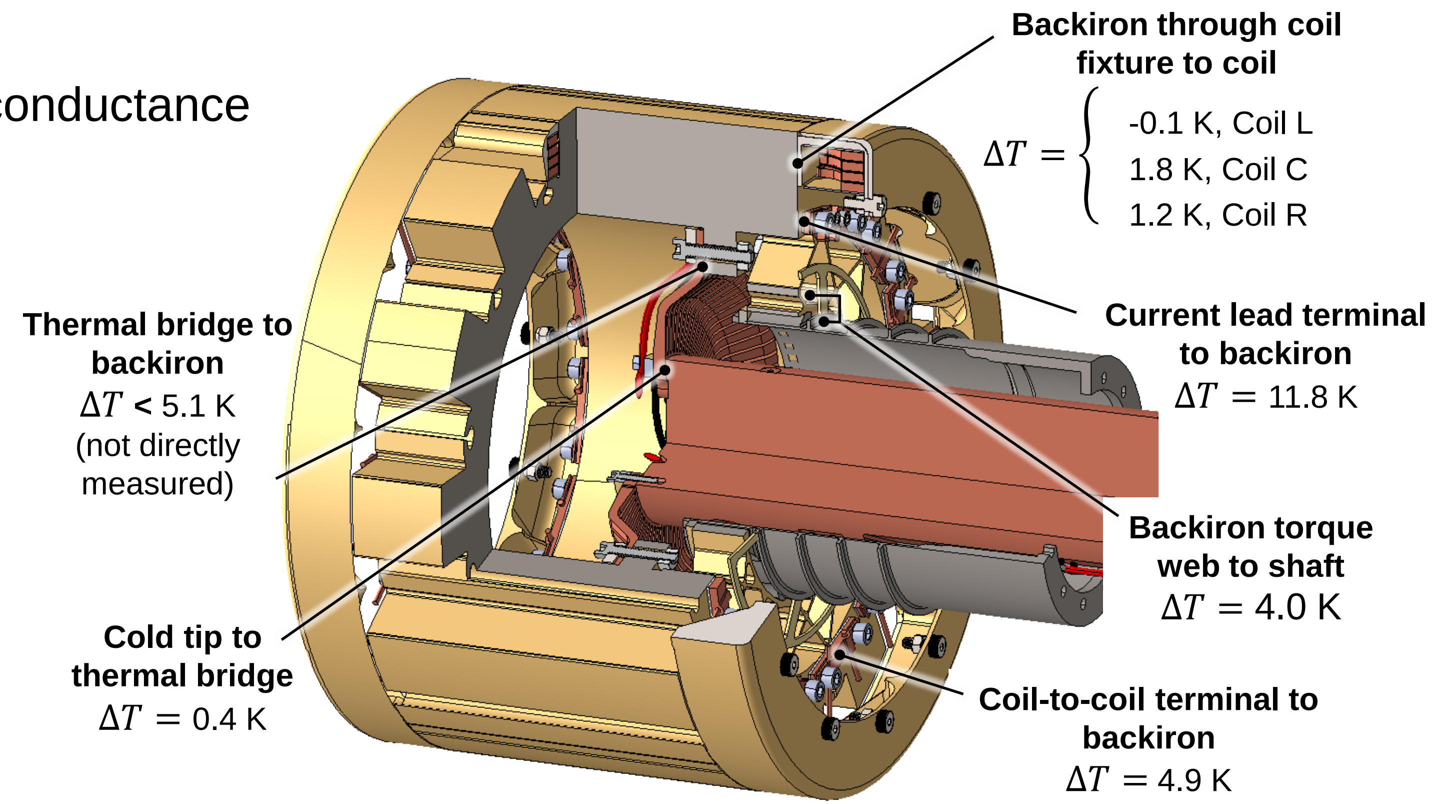
10. Scheidler, J.J. et al., IEEE Transactions on Applied Superconductivity, 2024. (to appear)
11. Scheidler, J.J. et al., Proc. of AIAA/IEEE Electric Aircraft Technologies Symposium, 2023.
12. Stalcup, E.J. et al., Thermal & Fluids Analysis Workshop (TFAWS), 2023.

Recent Progress on HEMM Rotor

- Took ~8 hours to cool down from room temperature to 50 K
- Observed ΔT from cryocooler's cold tip to coils (10.9 to 12.3 K) is acceptable but provides little to no margin
- Correlation to thermal model suggests opportunities for improvement, but a repeat test with additional temperature sensors would be needed to confirm & demonstrate those ideas
    - RMS modeling error reduced from 11.4 K to 4.5 K
    - Improve current lead thermal sinking
    - Potentially improve thermal bridge contact conductance and/or PVD gold emissivity
    - Post-test emissivity measurements planned



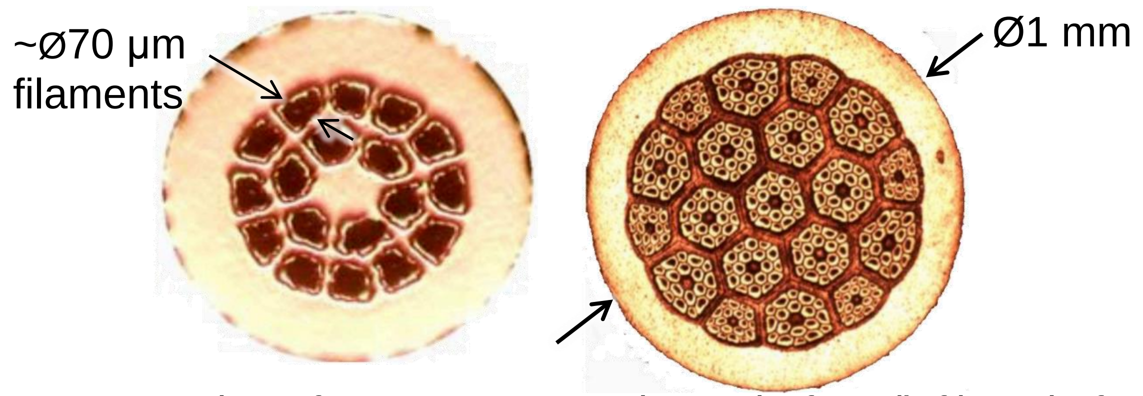
Transient response of HEMM rotor in ICE-Box



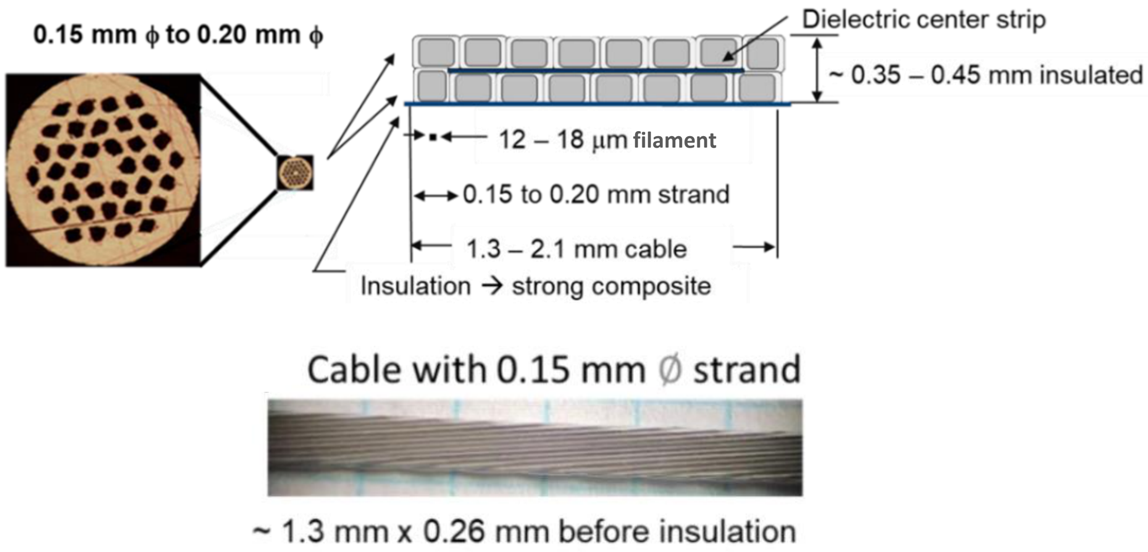
Temperature gradient across key interfaces

Recent Progress on Superconductor Development

- Superconductors only loss-free under DC current and magnetic field
  - Existing superconductors are suitable for the field windings of a machine (often on the rotor) but not for the armature windings (often on the stator)
- NASA funded multiple SBIR projects to develop low AC loss versions of MgB_2 and Bi-2212 superconductors [13,14]
  - Performance is now viable for superconducting machines, but further experimental validation is required



Cross-section of MgB_2 superconductor before (left) and after (right) NASA-funded development to reduce AC loss [13]



16 wire Bi-2212 superconducting cable [14]

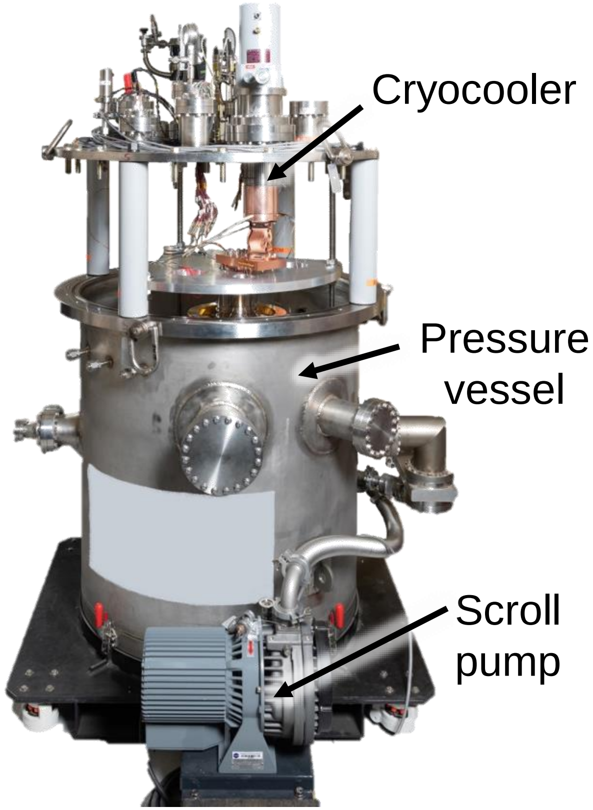
13. Brown, G.V. et al., NASA/TM-20205005815, 2020.
14. Otto, A. et al., Proc. of AIAA Aviation Forum, 2023.

NASA’s Superconducting Test Facilities

Multi-purpose cryogenic vacuum chambers

ICE-Box

- Wide range of test articles – single wires to components or assemblies up to about Ø0.75 m x 1 m
- Current vacuum capability: ~10^{-3} torr (warm) to ~10^{-5} torr (cold)
- Cryocooler Lift Capacity
  - Primary AL-325:
    79W @ 20K
    or 100W @ 25K
  - Designed for secondary / cold wall cryocooler, but not currently installed
- Inert gas backfill capable



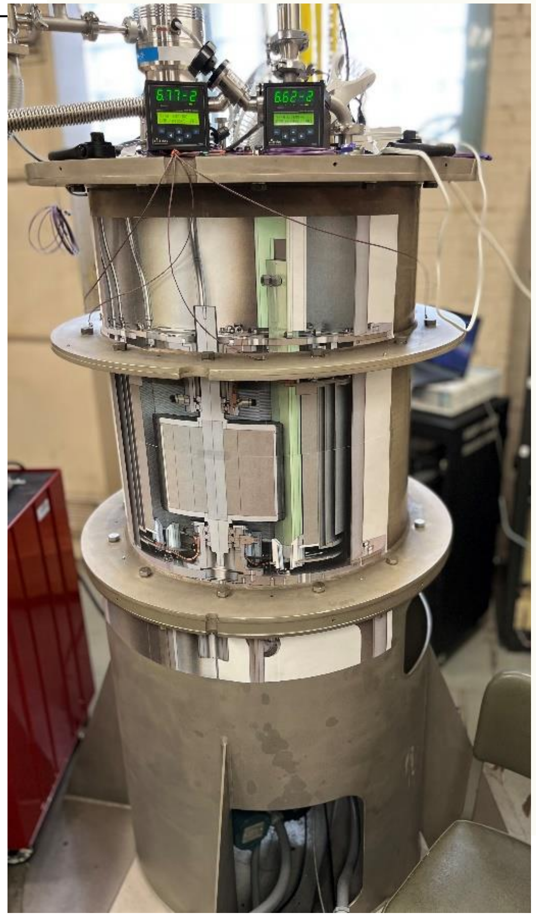
VF-15

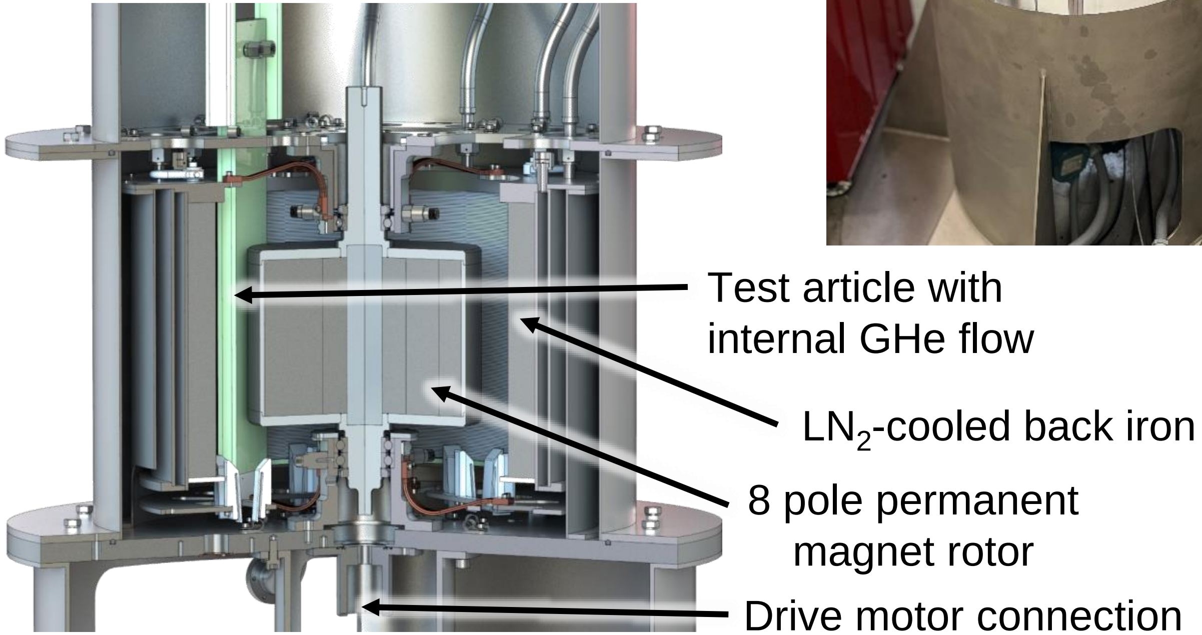
- Test articles up to about Ø0.4 m x 0.4 m
- Vacuum capability: 10^{-6} torr (warm)
- Cryocooler Lift Capacity: 79W @ 20K or 100W @ 25K

NASA's Superconducting Test Facilities

AC loss test rig

- Superconducting Coil Tester creates realistic environment for a stator coil
  - ~20 K and up
  - 0-400 Hz electrical frequency
  - 0.4-0.5 T magnetic field produced by spinning rotor
  - Test article cooled with cryocooled gaseous He (GHe)
  - Loss target: ~5 – 50 W
  - Expected tare: < 2 W





Vertical Lift Aircraft
Electric Motor Reliability & Electrical Power Quality

Vertical Lift Propulsion "Technical Challenge"

"Reliable and Efficient Propulsion Components for UAM"

Because there is a lack of data for propulsion systems and thermal management systems for UAM vehicles, NASA will

- develop design and test guidelines,
- acquire data,
- and explore new concepts

that improve propulsion system component reliability, culminating by demonstrating 2-4 orders of magnitude improvement in 100kW-class electric motor reliability

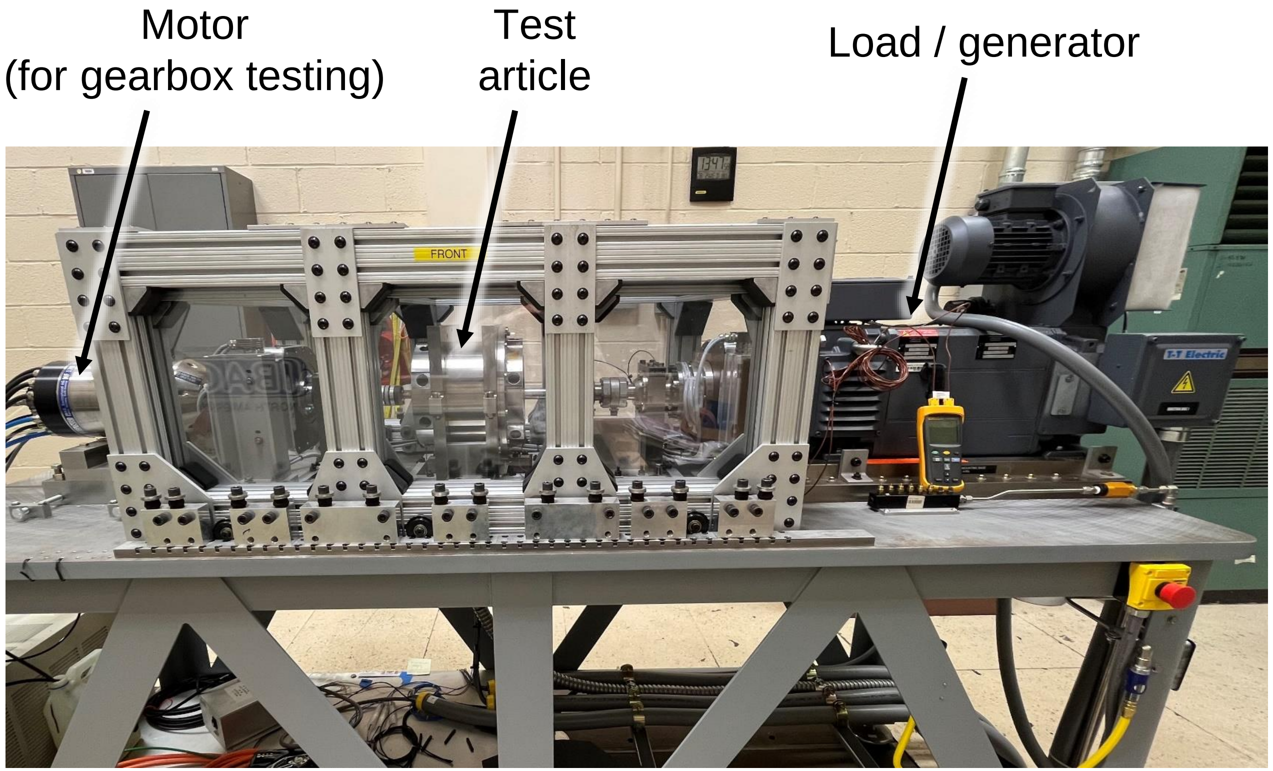
Ongoing work [15,16]

- Analysis of a motor winding's thermal and electrical loading over representative flight profiles
- Motor reliability modeling
- Development of fault tolerant motors
- Testing of thermochemical aging, mechanical aging, and partial discharge of statorettes

15. Tallerico, T. et al., NASA/TM-20220004926, 2022.
16. Tallerico, T.F. et al., Proc. of IEEE International Electric Machines & Drives Conference, 2023.

NASA Glenn's E-Drives Rig

- Scope
  - Test gearboxes (now) & motors and inverters (Summer '24)
  - Mechanical, electrical, vibration, & thermal measurements
- Key capabilities
  - Load: 238 Nm, 60 kW, 7,400 rpm plus 160% short duration overload
  - Motor (for gearbox testing): to 21,500 rpm input & 7,400 rpm output
  - DC power supply (for motor/inverter testing): 800 V, 125 A, 100 kW
  - Validation-quality data (very high precision – e.g., gearbox efficiency up to < ±0.2% with 95% confidence)
  - Directly measure temperature of energized motor windings (up to 1000 V RMS continuous)
  - Emulate rotor loads with new generator dynamometer
  - Year-round operation



Acknowledgements

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THANK YOU


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